

Energy and exergy assessments of a novel trigeneration system based on a solid oxide fuel cell



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ABSTRACT

Energy and exergy assessments are reported of a novel trigeneration system based on a solid oxide fuel cell (SOFC), for steady-state operation and using a zero-dimensional approach. The trigeneration system also includes a generator-absorber heat exchanger for cooling and a heat exchanger for the heating process. The influences of two significant SOFC parameters (current density and inlet flow temperature) on several variables are investigated. The results show that the energy efficiency is a minimum of 33% higher when using the trigeneration system compared with the SOFC power cycle. In addition, the maximum energy efficiencies are found to be 79% for the trigeneration system, 69% for the heating cogeneration, 58% for cooling cogeneration and 46% for electricity production. Moreover, the highest trigeneration exergy efficiency is almost 47% under the given conditions. It is also shown that, as SOFC current density increases, the exergy efficiencies decrease for the power cycle, cooling cogeneration, heating cogeneration and trigeneration. As current density increases, the trigeneration energy and exergy efficiencies decrease, and an optimal current density is observed to exist at which the net electrical power is a maximum. As SOFC inlet flow temperature increases, the trigeneration energy and exergy efficiencies and net electrical power increase to a peak and then decrease. The main exergy destructions occur in the air heat exchanger, the SOFC and the afterburner.

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1. Introduction

Accessibility of energy resources and global warming are two important long-term problems. Global energy demand has steadily risen over time, notwithstanding the limited availability of non-renewable fossil fuels. As a consequence, more efficient and clean energy systems are being sought. The energy efficiency of conventional power plants based on single prime mover is usually less than 40%, with most of the energy loss associated with waste heat. Combining cooling and heating subsystems in a conventional plant can increase the system efficiency considerably, and energy efficiencies can reach 80% through trigeneration [1,2], the simultaneous production of cooling, heating and electricity, often from one energy source. Trigeneration, also referred to as a combined cooling, heating and power (CCHP), offers a number of potential benefits:

- Increased efficiency.
- Reduced fuel and energy costs.
- Significantly reduced greenhouse gas emissions.
- Shortened transmission lines.
- Fewer distribution units.
- Increased power supply reliability.

The primary driver is an important part of a trigeneration system, making its selection important. The main primary drivers are gas turbines, steam turbines, external combustion engines, internal combustion engines, micro-turbines, and fuel cells. Among these, trigeneration based on fuel cells often achieves higher energy efficiency, in part because the fuel cell avoids Carnot efficiency limitations.

The solid oxide fuel cell (SOFC) is considered an important emerging technology. It can produce electricity directly from a fuel, such as methane, and an oxidant, such as air. It operates at high temperatures and generates much waste heat, so it is commonly coupled with a gas turbine (GT) or an organic Rankine cycle (ORC) as a bottom cycle to improve the overall efficiency by

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Nomenclature

a	activity factor of species in electrochemical reaction	<i>Greek letters</i>	
A_a	active surface area, m^2	η	energy efficiency
D_{aeff}	effective gaseous diffusivity through anode, m^2/s	ψ	exergy efficiency
D_{ceff}	effective gaseous diffusivity through cathode, m^2/s	ρ	electrical resistivity of cell components
$\bar{ex}_i^{ch,0}$	standard chemical exergy of species, kJ/mol		
$\dot{Ex}$	exergy rate, kW	<i>Subscripts</i>	
$\dot{Ex}^{ch}$	rate of chemical exergy, kW	0	atmospheric condition
$\dot{Ex}^{ph}$	rate of physical exergy, kW	a	anode
F	Faraday constant, C/mol	abs	absorber
Δg^0	change in molar Gibbs free energy, J/mol	ac	AC current, air compressor
GAX	generator absorber heat exchanger	act	activation
$\bar{h}$	molar enthalpy, J/mol	AHE	air heat exchanger
I	current, A	c	cathode
$\dot{I}$	exergy destruction rate, kW	cog,c	cooling cogeneration
j	current density, A/m^2	cog,h	heating cogeneration
j_{as}	anode-limiting current density, A/m^2	conc	concentration
j_{cs}	cathode-limiting current density, A/m^2	cond	condenser
j_{oa}	exchange current density of anode, A/m^2	cv	control volume
j_{oc}	exchange current density of cathode, A/m^2	des	desorber
K	equilibrium constant of waste gas shift reaction	e	electrolyte, exit
L	thickness of SOFC layer, m	el	electrical power
LHV	lower heating value, kJ/mol	evap	evaporator
$\dot{n}$	molar flow rate, mol/s	fc	fuel compressor
N_{FC}	total number of fuel cells	FC	fuel cell
$\dot{Q}$	heat rate, kW	FHE	fuel heat exchanger
$\bar{R}$	universal gas constant, $J/mol K$	h	heating
$R_{contact}$	contact resistivity, Ωm^2	HR	heat recovery
$r_{el,h}$	electrical to heating ratio	in	inlet
$r_{el,c}$	electrical to cooling ratio	int	interconnect
$\bar{s}$	molar entropy, $J/mol K$	inv	DC to AC inverter
T	temperature, K	ohm	ohmic
U_f	fuel utilization ratio	N	Nernst
U_o	air utilization ratio	tri	trigeneration
V	voltage, V	WHE	water heat exchanger
$\dot{W}$	power, kW	wp	water pump
$\dot{W}_{FC,stack}$	power output of fuel cell	–	molar
x_r	extent of steam reforming reaction for methane, mol/s	.	rate
y_i	molar concentration	0	standard pressure
y_r	extent of water gas shift reaction, mol/s	ch	chemical
z_r	extent of electrochemical reaction, mol/s	ph	physical

recovering SOFC waste heat. Many researchers have studied the performance of SOFC-GT hybrid power plants [3–16], integrated SOFC-ORC power plants [17,18] and combined SOFC-Stirling hybrid plants [19]. Few analyses, however, have been reported of trigeneration power plants based on an SOFC. Some of the more significant of these are now described.

Weber et al. [20] conducted detailed CO_2 emission and cost analyses of a trigeneration system based on a SOFC primary mover in an office building, and demonstrated that the system reduced CO_2 emissions by 30% at a cost increase of 70% compared with a conventional system.

A trigeneration plant driven by a SOFC and a gas turbine was studied by Burner et al. [21]. The plant included half-, single- and double-effect chillers, a heat pump, an additional gas boiler, a heat recovery boiler, a compression chiller and cooling system. They considered the potential of combining a heat pump into the trigeneration system. The study considered energy and exergy efficiencies and concentrated on costs and CO_2 emissions, and demonstrated that the SOFC-GT system is attractive economically and environmentally. The study utilized multi-objective optimization

based on a multi-criteria evolutionary algorithm, and incorporated the following optimization objectives: annual total cost of trigeneration and annual CO_2 emission rates.

Liu et al. [22] proposed a trigeneration plant by combining an internal-reforming solid oxide fuel cell (IRSOFC) with a zeolite/water adsorption chiller, and analyzed numerically the performance of the system under various operating conditions and parameters.

Yu et al. [23] analyzed a total energy system incorporating a SOFC and an absorption chiller driven by exhaust gas to provide electricity, cooling and/or heating simultaneously. They found that, as fuel utilization coefficient varies, both the electrical efficiency and total efficiency of the system achieved maximum values.

Al-Sulaiman et al. [24] carried out an energy analysis of a trigeneration system based on a SOFC and an ORC. The system also consisted of a heating process and a single-effect absorption chiller. The analysis demonstrated that, compared to only a power plant, trigeneration increases the efficiency by at least 22%. They also found that the exergy efficiency increased by 3–25% when trigeneration was applied [25].

- The refrigerant is saturated at the channel exits of the condenser and the evaporator.
- The solutions at the channel exits of the absorber and the generator are at equilibrium and they are at the corresponding device temperatures.
- Pressure drops due to friction in heat exchangers and in the connecting pipelines are neglected.
- The approach temperature at either end of the GAX heat exchanger is assumed to be 0 K.
- The system rejects heat to cooling water at the condenser and absorber.

4. Modeling and analysis

In this section, the modeling of the SOFC system, and the energy and exergy analyses of the considered trigeneration system, are described. The Engineering Equation Software (EES) is applied solve the resulting equations.

4.1. Input data

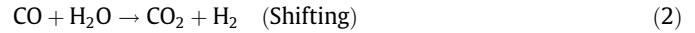
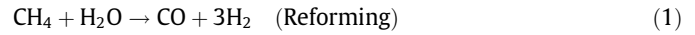
The input data applied in the analysis are listed in Table 1.

4.2. SOFC modeling

For a methane fueled SOFC system, either an internal or external reformer is used. An internal reformer is usually superior because of its relatively low cost. The SOFC model is presented in the following two subsections.

4.2.1. Reformer model

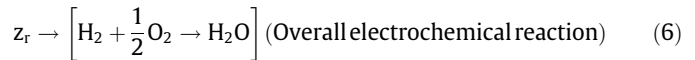
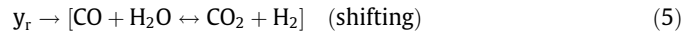
The ability of an SOFC system to simultaneously utilize hydrogen and carbon monoxide as fuel is an important characteristic. Through direct internal reforming inside the fuel cell, carbon monoxide and methane result as a fuel mixture. The reactions that occur in the internal reformer are mainly endothermic, and attain the needed heat from the fuel cell. The use of an internal reformer reduces the dependence of the fuel cell on a cooling system. The following chemical reactions occur in the internal reformer [4]:



Eq. (1) depicts the steam reforming in which methane is converted to hydrogen. Eq. (2) presents the water–gas shift reactions. The hydrogen obtained from these reactions is used in the following relation electrochemical reaction the fuel cell:



The mechanisms of the chemical and electrochemical reactions occurring at the anode and the cathode of the fuel cell are based on the following equilibrium equations [4]:



The molar conversion rates for Eqs. (4) and (5) are x_r , y_r , and z_r , respectively.

Table 1
Input data.

SOFC system [28]	Temperature difference between SOFC inlet and exit	100 K
	Fuel utilization factor	0.85
	Active surface area	0.01 m ²
	Baseline current density	8000 A/m ²
	DC–AC inverter efficiency	0.97
	Base inlet temperature to SOFC	1000 K
	Exchange current density of anode	6500 A/m ²
	Exchange current density of cathode	2500 A/m ²
	Effective gaseous diffusivity through anode	0.2 × 10 ^{−4} m ² /s
	Effective gaseous diffusivity through cathode	0.05 × 10 ^{−4} m ² /s
	Thickness of anode	0.05 × 10 ^{−2} m
	Thickness of cathode	0.005 × 10 ^{−2} m
	Thickness of electrolyte	0.001 × 10 ^{−2} m
	Thickness of interconnect	0.3 × 10 ^{−2} m
	Fuel compressor isentropic efficiency	0.85
	Air compressor isentropic efficiency	0.85
	Pump isentropic efficiency	0.85
	Number of cells	11,000
	Steam-to-carbon ratio	2.5
	Afterburner combustion efficiency	99%
	Fuel cell pressure drop	2%
	Afterburner pressure drop	3%
	Pressure drops for heat exchangers	2%
	Efficiency of solution pump	50%
GAX system [29]	Effectiveness of heat exchanger	80%
	Degassing value	0.3
Heating process heat exchanger (Heat recovery)	Effectiveness of heat exchanger	75%
	Pressure drop	3%
Ambient condition	Ambient temperature	298.15 K
	Ambient pressure	101.3 kPa
Standard chemical exergy Szargut [30]	CH ₄	831.6 kJ/mol
	CO ₂	19.87 kJ/mol
	CO	275.1 kJ/mol
	N ₂	0.72 kJ/mol
	O ₂	3.97 kJ/mol
	H ₂	236.1 kJ/mol
	H ₂ O (g)	9.5 kJ/mol

The fuel utilization factor and the air utilization ratio respectively can be defined as

$$U_F = \frac{(\text{Fuel})_{\text{consumed}}}{(\text{Fuel})_{\text{supplied}}} = \frac{(\text{H}_2)_{\text{consumed}}}{(\text{H}_2)_{\text{supplied}}} = \frac{z_r}{3x_r + y_r} \quad (7)$$

$$U_o = \frac{(\text{Air})_{\text{consumed}}}{(\text{Air})_{\text{supplied}}} = \frac{(\text{O}_2)_{\text{consumed}}}{(\text{O}_2)_{\text{supplied}}} = \frac{z_r/2}{\dot{n}_{\text{O}_2,3}} \quad (8)$$

By applying mass balances to Eqs. (4)–(6), the molar flow rates $\dot{n}$ of the flowing gases can be determined as follows:

$$\dot{n}_{\text{CH}_4,11} = x_r$$

$$\dot{n}_{\text{H}_2\text{O},11} = r_{\text{sc}} \cdot \dot{n}_{\text{CH}_4,11} = 2.5x_r$$

$$\dot{n}_{\text{H}_2,12} = 3x_r + y_r - z_r$$

$$\dot{n}_{\text{CO},12} = x_r - y_r$$

$$\dot{n}_{\text{CO}_2,12} = y_r$$

$$\dot{n}_{\text{H}_2\text{O},12} = \dot{n}_{\text{H}_2\text{O},11} - x_r - y_r + z_r = 1.5x_r - y_r + z_r$$

$$\dot{n}_{\text{O}_2,3} = \frac{z_r}{2U_o}$$

$$\dot{n}_{\text{O}_2,4} = \dot{n}_{\text{O}_2,3} - \frac{z_r}{2} \quad (9)$$

$$\dot{n}_{\text{N}_2,3} = \frac{79}{21} \times \dot{n}_{\text{O}_2,3}$$

$$\dot{n}_{\text{N}_2,4} = \dot{n}_{\text{N}_2,3}$$

$$\dot{n}_3 = \dot{n}_{\text{O}_2,3} + \dot{n}_{\text{N}_2,3}$$

$$\dot{n}_4 = \dot{n}_{\text{O}_2,4} + \dot{n}_{\text{N}_2,4}$$

$$\dot{n}_{11} = \dot{n}_{\text{H}_2\text{O},11} + \dot{n}_{\text{CH}_4,11}$$

$$\dot{n}_{12} = \dot{n}_{\text{H}_2,12} + \dot{n}_{\text{H}_2\text{O},12} + \dot{n}_{\text{CO},12} + \dot{n}_{\text{CO}_2,12}$$

The constants x_r and y_r are calculated using the equilibrium constant and current relations. The equilibrium constant for shift reaction can be written as

$$\ln K_s = -\frac{\Delta \bar{g}_s^o}{\bar{R} \cdot T_{\text{FC},e}} = \ln \left[\frac{y_r \times (3x_r + y_r - z_r)}{(x_r - y_r) \times (1.5x_r - y_r + z_r)} \right] \quad (10)$$

where $\bar{R}$, $T_{\text{FC},e}$ and $\Delta \bar{g}_s^o$ are the universal gas constant (8.314 J/[mol K]), the temperature at the exit of the SOFC and the Gibbs free energy, respectively. The latter quantity for the shift reaction can be written as

$$\Delta \bar{g}_s^o = \bar{g}_{\text{s,CO}_2}^o + \bar{g}_{\text{s,H}_2}^o - \bar{g}_{\text{s,H}_2\text{O}}^o - \bar{g}_{\text{s,CO}}^o \quad (11)$$

where

$$\bar{g}_s^o = \bar{h} - T_{\text{FC},e} \bar{s}^o \quad (12)$$

In Eq. (12), $\bar{h}$ and $\bar{s}^o$ are the enthalpy per molar flow rate and the standard entropy per molar flow rate respectively. For ideal gases, $\bar{h}$ is function of temperature and $\bar{s}^o$ is a function of temperature and standard pressure (101.3 kPa).

The resulting current I and current density j respectively can be evaluated as follows:

$$I = j \cdot A_a \quad (13)$$

$$j = \frac{2 \cdot F \cdot z_r}{N_{\text{FC}} \cdot A_a} \quad (14)$$

where A_a , F and N_{FC} denote the active surface area, the Faraday constant (96,485 C/[g mol]) and the number of cells.

The work rate produced by the SOFC stack $\dot{W}_{\text{FC,stack}}$ can be expressed as

$$\dot{W}_{\text{FC,stack}} = N_{\text{FC}} \cdot I \cdot V_c \quad (15)$$

where V_c is cell voltage, defined as

$$V_c = V_N - V_{\text{loss}} \quad (16)$$

Here, V_N is the Nernst voltage and V_{loss} the voltage loss, which is the sum of three separate voltage losses (activation, ohmic, and concentration). That is, the voltage loss can be written as

$$V_{\text{loss}} = V_{\text{ohm}} + V_{\text{act}} + V_{\text{conc}} \quad (17)$$

The calculations of the Nernst voltage and the voltage losses are described in Table 2. There, ρ , L , R_c , j_{oa} , j_{oc} , D_{ceff} and D_{aef} denote electrical resistivity of a cell component, thickness of a cell component, resistivity contact, exchange current density of anode, exchange current density of cathode, effective gaseous diffusivity through the cathode and effective gaseous diffusivity through the anode, respectively. Also, the subscripts *a*, *c*, *e*, *int*, *conc*, *act* and *ohm* denote anode, cathode, electrolyte, interconnect, concentration, activation and ohmic, respectively.

4.2.2. Validation of SOFC model

The experimental data with methane fuel as introduced by Tao et al. [34] are used to validate the proposed model. The validation is depicted in Table 3, which shows the changes of both cell voltage and power density with the current density. The model is seen to exhibit good agreement with the experimental data, with an error of less than 6%.

4.3. Energy analysis of system

At steady state and neglecting changes in kinetic and potential energy, an energy rate balance for a system component can be expressed as

$$\dot{Q} - \dot{W} = \sum_i \dot{n}_i \bar{h}_i - \sum_e \dot{n}_e \bar{h}_e \quad (18)$$

Table 2
Electrochemical equations.

Type	Equation
Nernst potential	$V_N = -\frac{\Delta \bar{g}_s^o}{2F} + \frac{\bar{R} T_{\text{FC},e}}{2F} \ln \left(\frac{a_{\text{H}_2,12} \cdot \sqrt{a_{\text{O}_2,4}}}{a_{\text{H}_2\text{O},12}} \right)$ $a_{\text{H}_2\text{O},12} = \frac{P_{\text{H}_2\text{O},12}}{P_{\text{ref}}} = \frac{y_{\text{H}_2\text{O},12} \cdot P_{12}}{P_{\text{ref}}}$ $a_{\text{H}_2,12} = \frac{P_{\text{H}_2,12}}{P_{\text{ref}}} = \frac{y_{\text{H}_2,12} \cdot P_{12}}{P_{\text{ref}}}, a_{\text{O}_2,4} = \frac{P_{\text{O}_2,4}}{P_{\text{ref}}} = \frac{y_{\text{O}_2,12} \cdot P_4}{P_{\text{ref}}}$ $\Delta \bar{g}_s^o = \bar{g}_{\text{H}_2\text{O}}^o - \bar{g}_{\text{H}_2}^o - \frac{1}{2} \bar{g}_{\text{O}_2}^o$ $\bar{g}^o = \bar{h} - T_{\text{FC},e} \cdot \bar{s}^o$
Ohmic loss [31]	$V_{\text{ohm}} = (R_c + \sum_i \rho_i L_i) \cdot j$ $\rho_e = (3.34 \times 10^4 \exp(-10300/T_{\text{FC},e}))^{-1}$ $\rho_a = (95 \times 10^6 / T_{\text{FC},e} \exp(-1150/T_{\text{FC},e}))^{-1}$ $\rho_c = (42 \times 10^6 / T_{\text{FC},e} \exp(-1200/T_{\text{FC},e}))^{-1}$ $\rho_{\text{int}} = (9.3 \times 10^6 / T_{\text{FC},e} \cdot \exp(-1100/T_{\text{FC},e}))^{-1}$
Activation polarization [32]	$V_{\text{act}} = V_{\text{act},a} + V_{\text{act},c}$ $V_{\text{act},a} = \frac{\bar{R} T_{\text{FC},e}}{F} \cdot \left(\sinh^{-1} \left(\frac{j}{j_{\text{oa}}} \right) \right)$ $V_{\text{act},c} = \frac{\bar{R} T_{\text{FC},e}}{F} \cdot \left(\sinh^{-1} \left(\frac{j}{j_{\text{oc}}} \right) \right)$
Concentration loss [33]	$V_{\text{conc}} = V_{\text{conc},a} + V_{\text{conc},c}$ $V_{\text{conc},a} = \frac{\bar{R} T_{\text{FC},e}}{2F} \cdot \left(\ln \left(1 + \frac{P_{\text{H}_2} j}{P_{\text{H}_2\text{O}} j_{\text{as}}} \right) - \ln \left(1 - \frac{j}{j_{\text{as}}} \right) \right)$ $V_{\text{conc},c} = -\left(\frac{\bar{R} T_{\text{FC},e}}{4F} \cdot \ln \left(1 - \frac{j}{j_{\text{cs}}} \right) \right)$ $j_{\text{as}} = 2 \cdot F \cdot P_{\text{H}_2} \cdot D_{\text{aef}} / \bar{R} \cdot T_{\text{FC},e} \cdot L_a$ $j_{\text{cs}} = 4 \cdot F \cdot P_{\text{O}_2} \cdot D_{\text{ceff}} / \left(\left(\frac{P_a - P_{\text{O}_2,4}}{P_a} \right) \bar{R} \cdot T_{\text{FC},e} \cdot L_c \right)$

Table 3

Comparison of present model results with results Tao et al. [34].

Current density (A/m ²)	Cell voltage (V) (Present work)	Cell voltage (V) (Tao et al.)	Power density (W/m ²) (Present work)	Power density (W/m ²) (Tao et al.)
0.2	0.79	0.76	0.158	0.15
0.3	0.711	0.68	0.216	0.21
0.4	0.644	0.62	0.253	0.26
0.5	0.56	0.57	0.288	0.295
0.6	0.51	0.52	0.3	0.315

where $\dot{Q}$, $\dot{W}$ and $\bar{h}$ denote heat transfer rate, work transfer rate and molar enthalpy, respectively. This equation states that the total rate at which energy enters the control volume equals the total rate at which it exits. The expressions applied to determine the energy efficiency of the system are presented in Table 4.

4.4. Exergy analysis of system

Exergy is defined as the maximum work obtainable from the combined system of a system plus its environment, as the system passes from a given state to the dead state while interacting with the environment only. Alternatively, exergy can be viewed as the minimum work input required to bring the system from the dead state to a given state. Unlike energy, exergy is not conserved but is destroyed by irreversibilities. The exergy associated with a material flow is the sum of its physical and the chemical exergy. That is,

$$\dot{E}x = \dot{E}x^{ph} + \dot{E}x^{ch} \quad (19)$$

where

$$\dot{E}x^{ph} = \sum_i \dot{n}_i ((\bar{h}_i - \bar{h}_0) - T_0(\bar{s}_i - \bar{s}_0)) \quad (20)$$

$$\dot{E}x^{ch} = \dot{n} \left(\sum_i y_i \bar{e}x_i^{ch,0} + \bar{R}T_0 \sum_i y_i \ln y_i \right) \quad (21)$$

In Eq. (20), $\bar{s}$ is molar entropy and in Eq. (21), $\bar{e}x_i^{ch,0}$ is the standard chemical exergy of a species, as presented by Szargut [30] and listed in Table 1.

The exergy rate balance of a control volume at steady state can be written as

$$\dot{I} = \sum_j \left(1 - \frac{T_0}{T_j} \right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{E}x_i - \sum_e \dot{E}x_e \quad (22)$$

where i denotes inlet and e denotes exit. Also, $\dot{Q}_j$ represents the rate of heat transfer at the location on the boundary where the instantaneous temperature is T_j . The accompanying exergy transfer rate can be evaluated as $(1 - T_0/T_j)\dot{Q}_j$. The term $\dot{E}x_i$ accounts for the exergy transfer rate accompanying mass flow and flow work at inlet i . Similarly, $\dot{E}x_e$ accounts for the exergy transfer rate accompanying mass flow and flow work at exit e . The flow exergy rates $\dot{E}x_i$ and $\dot{E}x_e$ are evaluated using Eqs. (21) and (22). In Eq. (22), one-dimensional flow is assumed at locations where mass enters and exits. Finally, the term $\dot{I}$ accounts for the exergy destruction rate due to irreversibilities within the control volume. In Eqs. (20)–(22), the subscript 0 denotes the value of a property at the surrounding conditions. The exergy efficiency relations for the system are listed in Table 5.

5. Results and discussion

The thermodynamic performance of the trigeneration system and the influence of variations of design parameters are examined. Since current density and inlet temperature to the SOFC significantly affect system performance parameters (e.g., energy and exergy efficiencies), we focus on them here.

Table 4

Energy efficiency definitions and system relations.

Input energy	$\dot{Q}_{in} = \dot{n}_{CH4,11} \cdot LHV_{CH4}$
Stack AC power of fuel cell	$\dot{W}_{FC,stack,ac} = \eta_{inv} \cdot \dot{W}_{FC,stack}$
Net electrical power of system	$\dot{W}_{net} = \dot{W}_{FC,stack,ac} - (\dot{W}_{wp,I} + \dot{W}_{ac} + \dot{W}_{fc} + \dot{W}_{mainpump} + \dot{W}_{wp,II})$
Fuel cell efficiency	$\eta_{FC} = \frac{\dot{W}_{FC,stack,ac} - (\dot{W}_{ac} + \dot{W}_{fc} + \dot{W}_{wp,I})}{\dot{Q}_{in}} \cdot 100$
Net electrical efficiency of system	$\eta_{el} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \cdot 100$
Heating cogeneration efficiency	$\eta_{cog,h} = \frac{\dot{W}_{net} + \dot{Q}_h}{\dot{Q}_{in}} \cdot 100$
Cooling cogeneration efficiency	$\eta_{cog,c} = \frac{\dot{W}_{net} + \dot{Q}_{eva}}{\dot{Q}_{in}} \cdot 100$
Trigeneration efficiency	$\eta_{tri} = \frac{\dot{W}_{net} + \dot{Q}_{eva} + \dot{Q}_h}{\dot{Q}_{in}} \cdot 100$
Electrical to heating ratio	$r_{el,h} = \dot{W}_{net} / \dot{Q}_h$
Electrical to cooling ratio	$r_{el,c} = \dot{W}_{net} / \dot{Q}_{eva}$

Table 5

Exergy efficiency definitions and relations for system.

Input exergy	$\dot{E}x_{in} = \dot{n}_{CH4,11} \cdot \bar{e}x_{CH4}^{ch,0}$
Exergy efficiency of SOFC system	$\psi_{FC} = \frac{(\dot{W}_{FC,stack,ac} - (\dot{W}_{wp,I} + \dot{W}_{ac} + \dot{W}_{fc} + \dot{W}_{wp,II}))}{\dot{E}x_{in}} \cdot 100$
Net electrical exergy efficiency	$\psi_{el} = \frac{\dot{W}_{net}}{\dot{E}x_{in}} \cdot 100$
Heating cogeneration exergy efficiency	$\psi_{cog,h} = \frac{\dot{W}_{net} + (\dot{E}x_{47} - \dot{E}x_{46})}{\dot{E}x_{in}} \cdot 100$
Cooling cogeneration exergy efficiency	$\psi_{cog,c} = \frac{\dot{W}_{net} + (\dot{E}x_{41} - \dot{E}x_{40})}{\dot{E}x_{in}} \cdot 100$
Trigeneration exergy efficiency	$\psi_{tri} = \frac{\dot{W}_{net} + (\dot{E}x_{47} - \dot{E}x_{46}) + (\dot{E}x_{41} - \dot{E}x_{40})}{\dot{E}x_{in}} \cdot 100$

5.1. Current density

The current density is an important parameter in cycle performance. Figs. 2–8 show the influence of current density on the voltage, efficiency, power output, electrical to heating and cooling ratios, methane inlet flow rate, exergy efficiency and exergy destruction rate, for a constant SOFC inlet flow temperature of 1000 K. In these figures, current densities from 5500 to 9500 A/m² are examined.

Fig. 2 indicates that the cell voltage V_c decreases and the total voltage loss V_{loss} increases as the current density increases. The total voltage loss is the sum of three voltage losses (activation polarization, ohmic and concentration), and the voltage losses are seen in Fig. 2 to be chiefly due to the activation polarization voltage loss.

Fig. 3 shows that the efficiency of the SOFC decreases as current density increases, mainly because the SOFC cell voltage decreases with increasing current density. Also, the net power efficiency is observed in this figure to decrease as current density increases. The maximum net electrical cycle efficiency is 46% at 5500 A/m² whereas the minimum is 31% at 9500 A/m². The highest cooling cogeneration (integration of SOFC with GAX) efficiency is 57% while the lowest is 48%. Conversely, the maximum heating cogeneration (integration of SOFC with heating load) efficiency, 67%, occurs at a current density of 5500 A/m² and the minimum, 60%, at a current density of 9500 A/m². Fig. 3 reveals that the highest

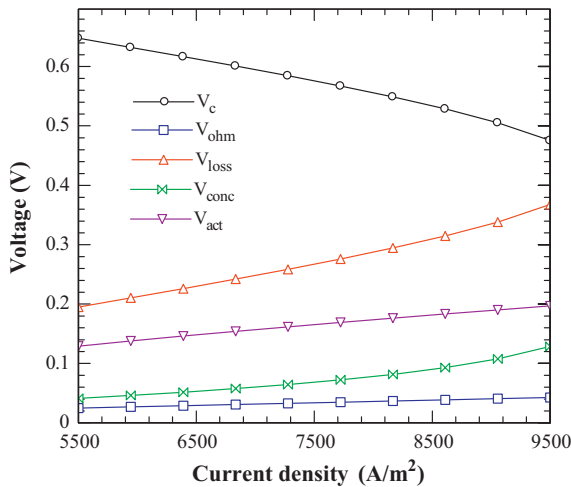


Fig. 2. Variation with current density of several fuel cell voltages at $T_i = 1000$ K.

and lowest trigeneration efficiencies are approximately 79% and 77%, respectively. It is also found that smallest gain in the efficiency of the trigeneration cycle compared with the net electrical efficiency is a considerable, at 33%.

The influence of the current density is shown in Fig. 4 of the powers produced by the fuel cell and consumed by the pump as well as by the compressors. For a constant fuel utilization factor and SOFC inlet temperature, increasing current density is associated with a linear increase of the fuel inlet molar flow rate (as shown in Fig. 5). That is, more chemical energy is converted to electrical energy and more cells current is produced. As the cell current increases and voltage decreases, a maximum SOFC-AC power output rate is thus obtained. It can be seen in Fig. 4 that, as current density increases, the net electrical power increases to a point and then decreases. There exists an optimal current density at which the maximum net electrical power is attained and, here, the maximum net electrical power is 421 kW at 8500 A/m². The electrical power use of the air compressor rises with current density due to increasing air flow rate through the compressor.

Fig. 6 illustrates the influence of the current density on the electrical to heating and cooling ratios. The electrical to heating ratio is seen to range from almost 4 at 5500 A/m² to 1.1 at 9500 A/m², while the electrical to cooling ratio varies from almost 4 at 5500 A/m² to 1.7 at 9500 A/m².

The effect of current density on exergy efficiency is shown in Fig. 7. The net electrical exergy efficiency is observed to decrease with increasing current density, primarily because cell voltage decreases and therefore power output from the SOFC decreases as the current density increases, as observed in Figs. 1 and 3. The net electrical exergy efficiency is declines from 44% to 29%, for the range of current densities considered. The cooling cogeneration exergy efficiency is around 0.5% higher than the net electrical exergy efficiency, mainly due to the small flows of cooling energy compared to electrical energy in the system. Also, the heating cogeneration exergy efficiency is seen in Fig. 7 to decline with increasing current density, and the maximum and minimum heating cogeneration exergy efficiencies are almost 46% and 32%, respectively. The trigeneration exergy efficiency is 0.5% or less higher than the heating cogeneration exergy efficiency. This efficiency increase is attributable to the small value of the cooling cogeneration exergy efficiency compared with the net electrical exergy efficiency.

The variation with current density of the exergy destruction rates in the main system components are given in Fig. 8, where all component exergy destruction rates are seen to rise with current density. The exergy destruction rates of the air compressor,

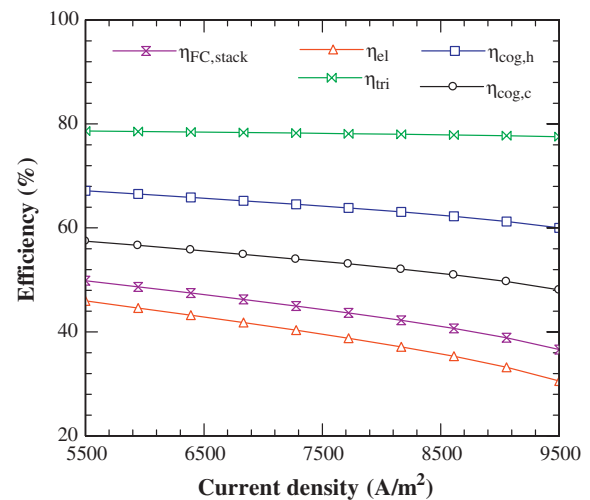


Fig. 3. Variation with current density of several system energy efficiencies at $T_i = 1000$ K.

the heat exchanger for the heating process, the absorber and desorber, the evaporator, the condenser and the fuel heat exchanger increase slightly (by less than 30 kW in total) as current density rises. But the variation in exergy destruction rate with current density is significantly more notable for other components, with the highest exergy destruction rates in the air heat exchanger and the SOFC. The maximum exergy destruction rate of the SOFC is 177 kW at 9500 A/m² and the minimum is 71 kW at 5500 A/m², while the exergy destruction of the air heat exchanger changes almost from 114 kW at 5500 A/m² to 302 kW at 9500 A/m².

5.2. SOFC inlet temperature

The effect of varying the SOFC inlet temperature on the performance of the trigeneration system is illustrated in Figs. 9–14, and is seen to differ from the effect of varying current density. The influence of SOFC inlet temperature is investigated here for a constant current density of 8000 A/m². Fig. 9 shows that, as SOFC inlet temperature increases, activation and concentration voltages increase but the ohmic voltage decreases, so the cell voltage increases to a point and then decreases. There exists an optimal SOFC inlet temperature at which a maximum cell voltage is attained and here the highest cell voltage is almost 0.59 V at 633 °C.

Fig. 10 indicates that as SOFC inlet temperature increases, the energy efficiency of the SOFC increases to a point and then decreases. This trend mimics that of the cell voltage with varying SOFC inlet temperature (see Fig. 9). The highest net electrical cycle efficiency is 41.0% at 633 °C while the lowest is 26.8% at 500 °C. The maximum cooling cogeneration (integration of SOFC with GAX) efficiency is 55.0% and the minimum is 47.0. Correspondingly, the highest and lowest heating cogeneration (integration of SOFC with heating load) efficiencies, 64.3% and 56.5%, are obtained at SOFC inlet temperatures of 633 °C and 500 °C, respectively. The maximum trigeneration efficiency is seen in Fig. 10 to be 78.3%.

The effect of varying SOFC inlet temperature on the powers produced by the fuel cell and consumed by the pump as well as by the compressors is depicted in Fig. 11. With increasing inlet temperature, the SOFC-AC output power increases to a maximum of 503 kW at 633 °C and decreases above this temperature. The reason for this trend is similar to that discussed above regarding the influence of varying current density on cell voltage. The maximum net electrical power is almost 450 kW at 633 °C.

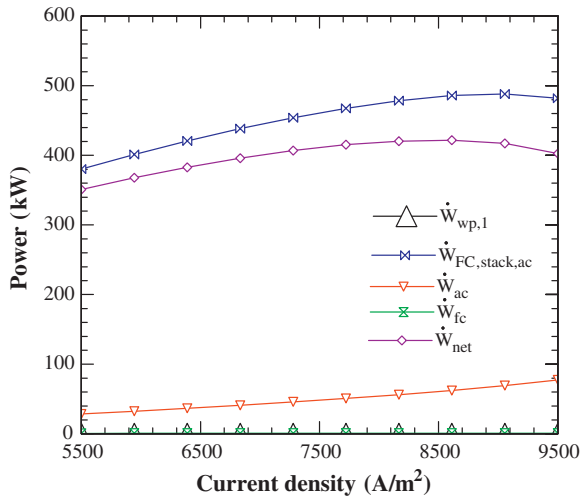


Fig. 4. Variation with current density of several power interactions at $T_i = 1000$ K.

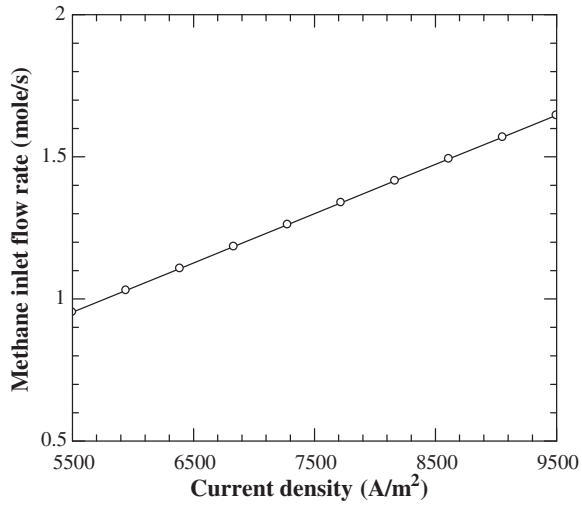


Fig. 5. Variation with current density of the methane inlet rate at $T_i = 1000$ K.

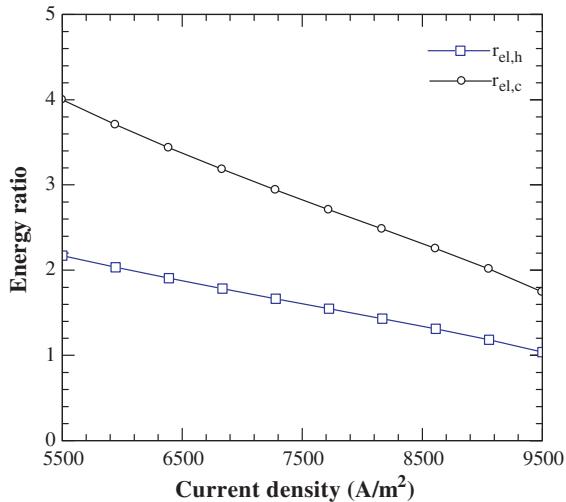


Fig. 6. Variation with current density of electrical to heating and cooling ratios at $T_i = 1000$ K.

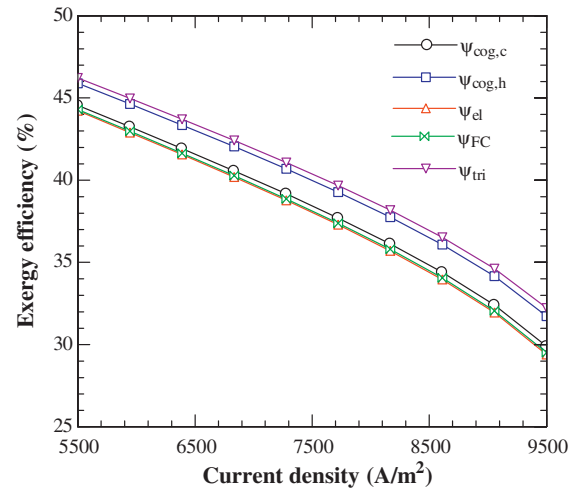


Fig. 7. Variation with current density of several system and component exergy efficiencies at $T_i = 1000$ K.

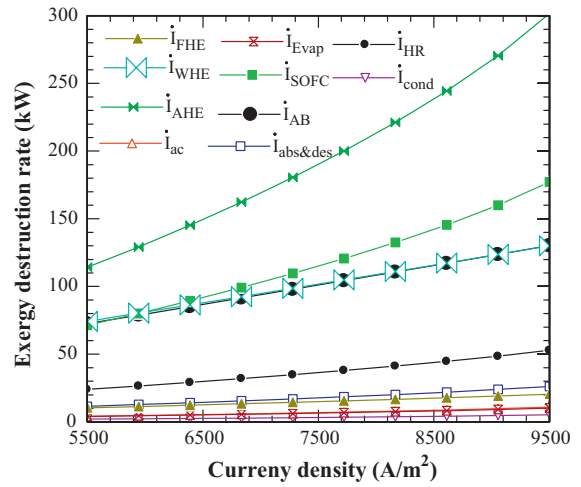


Fig. 8. Variation with current density of system and component exergy destruction rates at $T_i = 1000$ K.

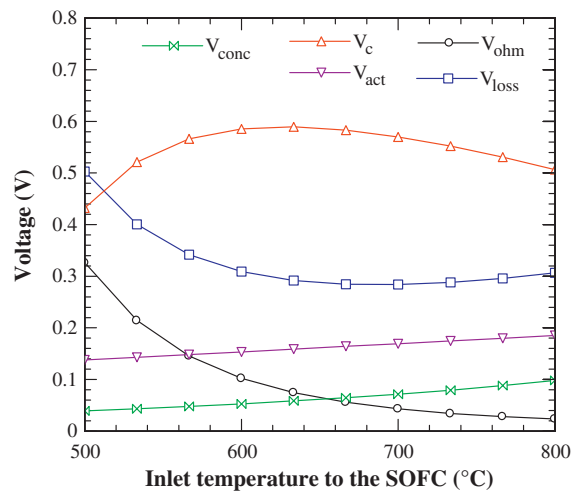


Fig. 9. Variation with SOFC inlet temperature of several voltages at $j = 8000$ A/m².

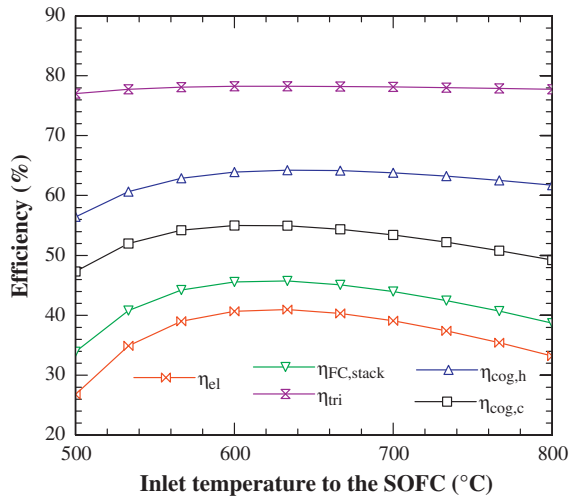


Fig. 10. Variation with SOFC inlet temperature of system and component energy efficiencies at $j = 8000 \text{ A/m}^2$.

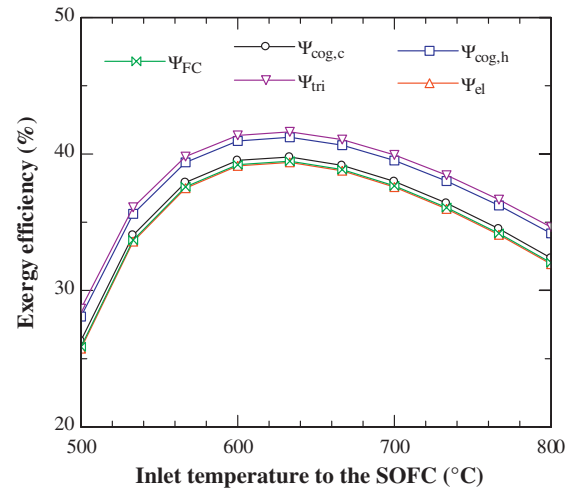


Fig. 13. Variation with SOFC inlet temperature of system and component exergy efficiencies at $j = 8000 \text{ A/m}^2$.

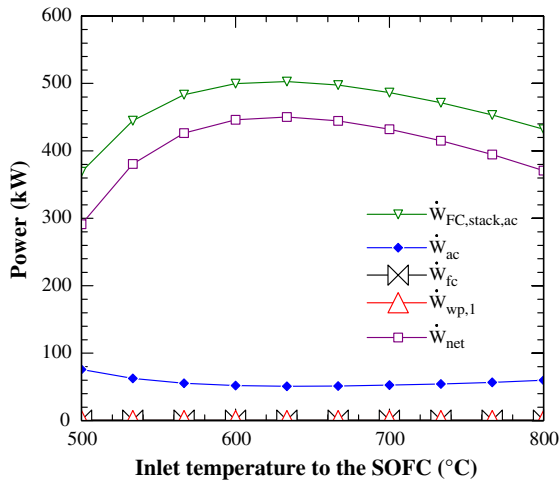


Fig. 11. Variation with SOFC inlet temperature of several power interactions at $j = 8000 \text{ A/m}^2$.

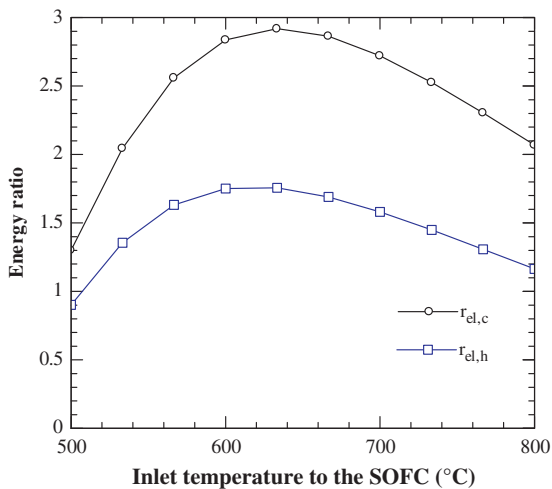


Fig. 12. Variation with SOFC inlet temperature of electrical to heating and cooling ratios at $j = 8000 \text{ A/m}^2$.

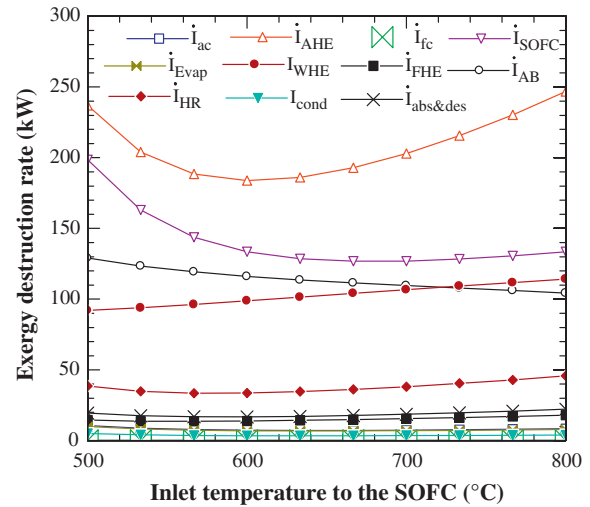


Fig. 14. Variation with SOFC inlet temperature of system and component exergy destruction rates at $j = 8000 \text{ A/m}^2$.

The effects of varying SOFC inlet temperature on the electrical to heating and cooling ratios are shown in Fig. 12. These variations exhibit similar trends, and the maximum electrical to heating and cooling ratios are observed to be 1.76 and 2.92, respectively.

The influence of SOFC inlet temperature on exergy efficiencies is shown in Fig. 13, where the trends exhibited for all cases shown are seen to be similar. Increasing SOFC inlet temperature t causes the exergy efficiencies to increase to a point and then decline. The maximum and minimum trigeneration exergy efficiencies are 42.6% and 28.7%, respectively.

The effect of varying SOFC inlet temperature on the exergy destruction rates of the main system components are illustrated in Fig. 14, where the maximum exergy destruction rates are seen to occur in the air heat exchanger and the SOFC. As SOFC inlet temperature increases, the exergy destruction of the SOFC decreases to a minimum value of 126.7 kW at 667 °C and then increases slightly.

6. Conclusions

The energy and exergy assessments performed of a novel tri-generation system based on solid oxide fuel cell (SOFC) under

steady-state operation and using a zero-dimensional approach provide useful insights. The influence is characterized of several design parameters such as SOFC current density, SOFC inlet flow temperature and fuel utilization factor on numerous performance parameters. Several significant conclusions can be drawn from results of this research:

- The energy analysis of the system demonstrates that trigeneration increases energy efficiency by at least 33% compared to a simple SOFC power cycle. That is, the maximum energy efficiency is 79% for the trigeneration system, 69% for heating cogeneration, 58% for cooling cogeneration and 46% for stand alone electricity generation.
- The highest trigeneration exergy efficiency is almost 47% for the given conditions, and the exergy efficiencies decrease for the power cycle, cooling cogeneration, heating cogeneration and trigeneration as the SOFC current density increases. Further, the trigeneration energy and exergy efficiencies decrease with current density, and the maximum net electrical power is achieved at an optimal current density. As SOFC inlet flow temperature increases, the trigeneration energy and exergy efficiencies and net electrical power increase to a maximum and then decrease.
- The main exergy destructions, which merit attention in efforts to improve system efficiency, occur in the air heat exchanger, the SOFC and the afterburner. Current density and SOFC inlet temperature significantly affect the exergy destruction rates in several of the main system components.

References

- [1] International Energy Agency. Combined heat and power: evaluating the benefits of greater global investment. France; 2008.
- [2] Kerr T. Combined heating and power and emissions trading: options for policy makers. International Energy Agency; 2008.
- [3] Massardo AF, Lubelli F. Internal reforming solid oxide fuel cell–gas turbine combined cycles (IRSOFC–GT): Part A – Cell model and cycle thermodynamic analysis. *ASME J Eng Gas Turb Power* 2000;122:27–35.
- [4] Chan SH, Ho HK, Tian Y. Modeling of simple hybrid solid oxide fuel cell and gas turbine power plant. *J Power Sources* 2002;111:320–8.
- [5] Calise F, Dentice d'Accadia M, Palombo A, Vanoli L. Simulation and exergy analysis of a hybrid solid oxide fuel cell (SOFC)–gas turbine system. *J Energy* 2006;31:3278–99.
- [6] Granovskii M, Dincer I, Rosen MA. Performance comparison of two combined SOFC–gas turbine systems. *J Power Sources* 2007;165(1):307–14.
- [7] Akkaya AV, Sahin B, Erdem HH. An analysis of SOFC/GT CHP system based on exergetic performance criteria. *Int J Hydrogen Energy* 2008;33(10):2566–77.
- [8] Lim TH, Song RH, Shin DR, Yang JI, Jung H, Vinke IC. Operating characteristics of a 5 kW class anode-supported planar SOFC stack for a fuel cell/gas turbine hybrid system. *Int J Hydrogen Energy* 2008;33(3):1076–83.
- [9] Haseli Y, Dincer I, Naterer GF. Thermodynamic modeling of a gas turbine cycle combined with a solid oxide fuel cell. *Int J Hydrogen Energy* 2008;33:5811–22.
- [10] Bao C, Shi YX, Croiset E, Li C, Cai NS. A multi-level simulation platform of natural gas internal reforming solid oxide fuel cell–gas turbine hybrid generation system: Part I. Solid oxide fuel cell model library. *J Power Sources* 2010;195:4871–92.
- [11] Inui Y, Matsumae T, Koga H, Nishiura K. High performance SOFC/GT combined power generation system with CO₂ recovery by oxygen combustion method. *J Power Energy Convers Manag* 2005;46(11–12):1837–47.
- [12] Zhang XW, Li J, Li GJ, Feng ZP. Cycle analysis of an integrated solid oxide fuel cell and recuperative gas turbine with an air reheating system. *J Power Sources* 2007;164:752–60.
- [13] Burbank Jr W, Witmera D, Holcomb F. Model of a novel pressurized solid oxide fuel cell gas turbine hybrid engine. *J Power Sources* 2009;193:656–64.
- [14] Zabihian F, Fung AS. Performance analysis of hybrid solid oxide fuel cell and gas turbine cycle: application of alternative fuels. *J Energy Convers Manag* 2013;76:571–80.
- [15] Bakalis DP, Stamatis AG. Full and part load exergetic analysis of a hybrid micro gas turbine fuel cell system based on existing components. *J Energy Convers Manag* 2012;64:213–21.
- [16] Caliendo P, Tock L, Ensinas AV, Marechal F. Thermo-economic optimization of a solid oxide fuel cell–gas turbine system fuelled with gasified lignocellulosic biomass. *Energy Convers Manage* 2014. <http://dx.doi.org/10.1016/j.enconman.2014.02.009>.
- [17] Akkaya AV, Sahin B. A study on performance of solid oxide fuel cell–organic Rankine cycle combined system. *J Energy Res* 2009;33(6):553–64.
- [18] Verda V. Solid oxide fuel cell system configurations for distributed generation. *J Fuel Cell Sci Technol* 2008;5(4).
- [19] Rokni M. Thermodynamic analysis of SOFC (solid oxide fuel cell) – Stirling hybrid plants using alternative fuels. *J Energy* 2013;61:87–97.
- [20] Weber C, Koyama M, Kraines S. CO₂-emission reduction potential and costs of a decentralized energy system for providing electricity, cooling and heating in an office-building in Tokyo. *J Energy* 2006;31(14):2705–25.
- [21] Burer M, Tanaka K, Favrat D, Yamada K. Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell–gas turbine combined cycle, heat pumps and chillers. *J Energy* 2003;28(6):497–518.
- [22] Liu Y, Leong KC. Numerical study of an internal-reforming solid oxide fuel cell and adsorption chiller co-generation system. *J Power Sources* 2006;159(1):501–8.
- [23] Yu ZT, Han JT, Cao XQ, Chen W, Zhang B. Analysis of total energy system based on solid oxide fuel cell for combined cooling and power applications. *Int J Hydrogen Energy* 2010;35(7):2703–7.
- [24] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Energy analysis of a trigeneration plant based on solid oxide fuel cell and organic Rankine cycle. *Int J Hydrogen Energy* 2010;35(10):5104–13.
- [25] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Exergy analysis of an integrated solid oxide fuel cell and organic Rankine cycle for cooling, heating and power production. *J Power Sources* 2010;195(8):2346–54.
- [26] Wang J, Yan Z, Ma S, Dai Y. Thermodynamic analysis of an integrated power generation system driven by solid oxide fuel cell. *Int J Hydrogen Energy* 2012;37(3):2535–45.
- [27] Ma S, Wang J, Yan Z, Dai Y, Lu B. Thermodynamic analysis of a new combined cooling, heat and power system driven by solid oxide fuel cell based on ammonia–water mixture. *J Power Sources* 2011;196(20):8463–71.
- [28] Ozgur Colpan C, Dincer I, Hamdullahpur F. Thermodynamic modeling of direct internal reforming solid oxide fuel cells operating with syngas. *Int J Hydrogen Energy* 2007;32(7):787–95.
- [29] Yari M, Zarin A, Mahmoudi SMS. Energy and exergy analyses of GAX and GAX hybrid absorption refrigeration cycles. *J Renew Energy* 2011;36(7):2011–20.
- [30] Szargut J. Exergy method technical and ecological applications. WIT Press; 2005.
- [31] U. G. Bossel. Final report on SOFC data facts and figures. Swiss Federal Office of Energy; 1992.
- [32] Kim JW, Virkar AV, Fung KZ, Mehta K, Sighal SC. Polarization effects in intermediate temperature, anode-supported solid oxide fuel cells. *J Electrochem Soc* 1999;146(1):69–78.
- [33] Chan SH, Low CF, Ding OL. Energy and exergy analysis of simple solid-oxide fuel-cell power systems. *J Power Sources* 2002;103(2):188–200.
- [34] Tao G, Armstrong T, Virkar A. Intermediate temperature solid oxide fuel cell (IT-SOFC) research and development activities at MSRI. In: Nineteenth annual ACERC and ICES conference, UT, USA; 2005.